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Schematic Feasibility Study of Bio-CCS Technology

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Abstract

Among in-situ microbes within depleted oil-gas reservoir, there are special species those produce much more methane gas in CO_2 rich environment than in CO_2 poor environment. CO_2 acts as a catalyst in the reaction. If we maintain preferable conditions for methanogenesis archaea during geological CCS, we will be able to abate greenhouse gas emission and produce natural gas as one of natural energy resources at the same time. We named the technological concept as 'Bio-CCS'. In Bio-CCS, CO_2 will be injected from a well for two purposes: to abate greenhouse gas emission and to cultivate methanogenic geo-microbes. CH_4 gas will be produced later using other wells. The procedure is similar to the Enhanced Oil/Gas Recovery (EOR/EGR) operation, but in Bio-CCS, the target is generation and production of methane out of depleted oil/gas reservoir during CO_2 abatement. We are evaluating the basic practicability of Bio-CCS that cultivate methanogenic geo-microbes within depleted oil/gas reservoirs for geological CCS, and produce methane gas as fuel resources on the course of CO_2 abatement for GHG control. While biologists are identifying the most effective cultivating conditions for methanogenic archaea, geologists, environmental scientists and system scientists are evaluating feasibilities of the technology concept. In this paper, we will introduce methodologies and interim results of our feasibility study on Bio-CCS.

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Keywords: Geological CO_2 sequenstration, CCS, risk assessment, software development, accident statistics, desaster rate, high-pressure gas;

1. Introduction

Depleted oil-gas reservoir is one of the candidates of CO_2 geological storage for the purpose of CO_2 abatement. Even in deep depleted oil/gas reservoirs, there are colonies of microbes. On the course of their biogenic activities, they resolve residual oil in

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depleted reservoir, and produce CH_4. Such species are called methanogenesis archaea. Some methanogenesis archaea produce much more methane gas in CO_2 rich environment than in CO_2 poor environment [1]. CO_2 acts as a catalyst in the reaction.

If we will be able to maintain preferable conditions for cultivation of methanogenesis archaea during geological CO_2 storage, we will be able to abate greenhouse gas (CO_2) emission and produce natural gas (CH_4) at the same time. We named the new concept as 'Bio-CCS'. In Bio-CCS, CO_2 will be injected for two purposes: to abate greenhouse gas emission; and to prepare preferable cultivating condition for methanogenic microbes to produce CH_4 gas as an energy resource. The procedure is similar to the Enhanced Oil/Gas Recovery (EOR/EGR) operation, but in Bio-CCS the target is depleted oil/gas reservoir. It is expected to produce methane gas out of during CO_2 abatement.

Aiming to evaluate the basic practicability of Bio-CCS, we started a feasibility study project named 'energy resources creation by combining geo-microbes and CCS'. In the project, while biologists are identifying the most effective cultivating conditions for methanogenic archaea, geologists, environmental scientists and system scientists are evaluating feasibilities of the technology concept. In this paper, we will describe interim results of our feasibility study on Bio-CCS.

2. Microbial reactions in depleted oil/gas reservoirs

In deep oil-gas reservoirs of thousand meters below from the surface, there are life activities of anaerobic microbial. When CO_2 is injected to a reservoir, it causes changes in pH, partial pressure of gasses, ingredients of water, and etc. As the result, constituent of microbial communities will change [2]. Dolphin analyzed chemical reactions those taken place during methanogenesis in depleted oil/gas reservoirs: oil-water mixture in depleted oil/gas reservoir contains acetate as ingredient; methanogens consume acetate and produce CH_4 [3].

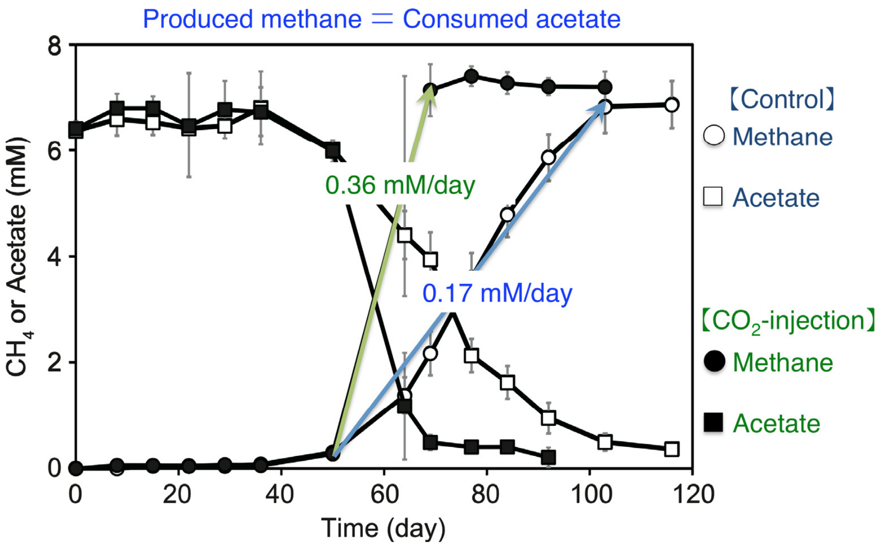


Figure 1 Methanogenesis in control and CO_2-injected microcosms [1].
Samples: In-situ water 800ml, clade oil 5ml.
Control: N_2 100%, CO_2-injected: N_2/CO_2 90:10.
Condition of incubation: 55ºc, 5MPa

Based on knowledge of previous studies, we examined relationship between reactions of in-situ microbial communities and CO_2 partial pressure in cultivation conditions. We collected bailed water samples from depleted oil reservoirs those containing in-situ microbes. Then cultivated them in laboratory. Among them, we obtained interesting results from bailed water from Yabase depleted oil-gas field in Japan. Depth of the reservoir was 1000-1300 m depth, and conditions were 53-65 ºC was 5MPa.

We prepared 1000 ml pressure containers to cultivate in a laboratory. In the containers, we poured 800 ml of bailed water samples as a source of indigenous microbes and 8ml of crude oil as nutrients. Then, we filled the container with either N_2 (100 %) or N_2/CO_2 (90:10) to analyze CO_2 effects on microbe microcosms. We kept containers in 55ºC, 5MPa to mimic in-situ conditions of depleted reservoirs, and measured concentrations of CO_2 and CH_4 partial pressures of the gas in the containers. We also conducted isotope tracer analysis in the course of the experiments. Then did molecular analyses and thermodynamic calculations.

Figure 1 shows relations between elapsed time (days) and concentrations (mM) of CO_2 and CH_4 in microcosms. Methanogenesis occurs under both controlled (N_2 100%) and CO_2-injected (N_2/CO_2 90:10) conditions. Comparing both results, methanogenesis rate in CO_2-injected condition (N_2/CO_2 90:10) was about twice than that controlled condition (N_2 100%) [1].

Based on isotope tracer analysis, molecular analyses and thermodynamic calculations, we find the difference of methanogenesis rate both in controlled and CO_2-injected conditions ware caused by different methanogen species: In oxidation control (N_2 100%) case, they starts from acetoclastic methanogenesis (2), and then proceeds to hydrogenotrophic methanogenesis (3); In CO_2-injected condition, other methanogen species those prefers CO_2 rich environment becomes active, and they oxidize acetate directly. CO_2 acts as a catalyst in the reaction.

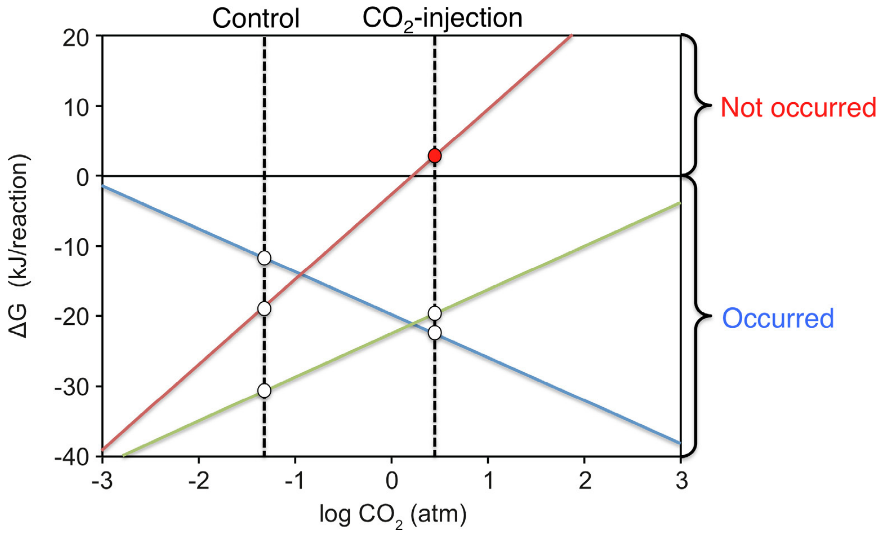


Figure 2 Thermodynamically explanation of relation between methanogenesis pass and CO_2 partial pressure [1].
When CO_2 isn't given (control), all three reactions will be taken place.
When CO_2 concentration is high (CO_2-injection),
acetoclastic methanogenesis (red) has positive delta G, and the reaction is restricted.
On the other hand, acetate oxidation has negative delta G, and the reaction proceed.

Oxidation of crude oil	$C_{16}H_{34}+16H_2O \rightarrow 8CH_3COO^- + 8H^+ + 17H_2$	(1)
Acetoclastic methanogenesis (red)	$CH_3COO^- + H^+ \rightarrow CH_4 + CO_2$	(2)
Hydrogenotrophic methanogenesis (blue)	$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$	(3)
Acetate oxidation (green)	$CH_3COO^- + H^+ + 2H_2O \rightarrow 4H_2 + 2CO_2$	(4)

3. Concept of Bio-CCS process

To evaluate the basic practicability of methanogen utilized CCS in depleted oil-gas reservoirs; we developed a concept of combination of CCS and reactions of methanogen, and named it Bio-CCS (See Figure 3)[4]. CO_2 will be injected from a well to abate greenhouse gas emission and to cultivate methanogenic geo-microbes; CH_4 will be produced from other well. The process is similar to enhanced oil/gas recovery (EOR/EGR), but in the case of Bio-CCS, the target is to produce and to product methane gas out of depleted oil/gas reservoir during CO_2 abatement. Table 1 shows conditions of conceptual 'Bio-CCS' site. As physical specifications of reservoir, we set almost same values measured in depleted oil reservoir described in previous section. CH_4 production rate in Table 1 is acetoclastic methanogenic process in CO_2 rich which was described in previous section.

To evaluate feasibility of Bio-CCS concept, we have to estimate: CH_4 generation volume, environmental impact along with life cycle of injection well, and risk-benefit balance of the Bio-CCS. For that purpose, we assumed two conceptual sites of Bio-CCS: One is depleted oil field and the other one is depleted gas field.

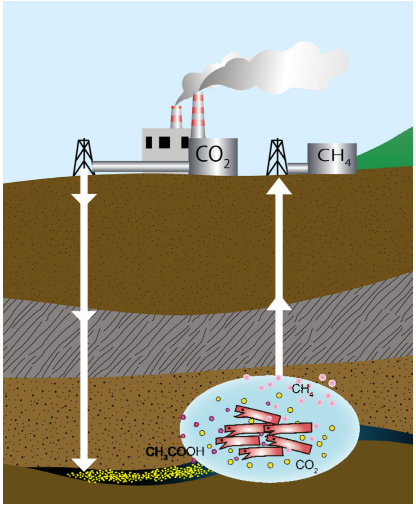


Figure 3 Conceptual process of 'Bio-CCS' site.

Table 1 Conditions of conceptual 'Bio-CCS'

Items	Spec
Reservoir	Depth: 1000 - 1300m Pressure: 5Mpa Temperature: 55ºC Permeability 1.0μm^2
CO_2 absorbent	Amine
CO_2 source	Fire power plant / oil-gas refinery
CO_2 transportation	Gas pipeline / Land transportation of CO_2 lq
CO_2 injection rate	1 ~ 10^5 ton /year
Injecting CO_2	Super critical CO_2
CH_4 producing rate	0.36 ± 0.04 m mol/day/litter water

4. Construction of Bio-CCS geological model and numerical analysis

When we judge feasibility of Bio-BBS technology concept, the most essential information is CH_4 generation potential. We developed a basic geological model of Bio-CCS process on CHEM-TOUGH simulator (Figure 4), and implemented microbial activities and CCS process into it [5].

For mineralogical composition of rock matrix, we applied Nagaoka's data. Concerning to formation water in depleted reservoir, we used compositions measured in-situ environment in Yabase during formation water sampling. We assumed a fluid flow model; 0.2 real pore space for reservoir matrix; 0.1 real pore space is occupied by residual oil; we regarded residual oil as part of matrix and it will not move; fluid will flow in the rest, 0.1 real pore space.

Using the model, we estimated mass distribution along with progress of Bio-CCS process. Figure 5 shows results of preliminary calculation with a scenario: CO2 is injected for 10 years in 104 ton/year rate; then the reservoir was left still for 90 years to allow microbes activities. Figure 5 shows mass distributions at 74.2 years after injection.

We roughly evaluated quantities of produced methane gas of this scenario and obtained tens tons of methane for 105 tons CO2 injection. In this scenario's case, produced CH4 is little.

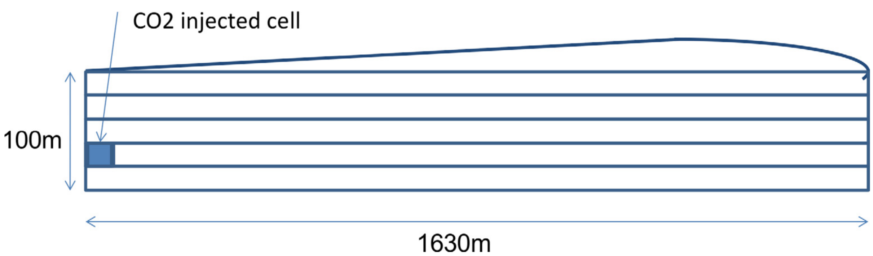


Figure 4 Reservoir model.
Depth of top and bottom of the model were -1000m and -1100m from the surface, respectively.

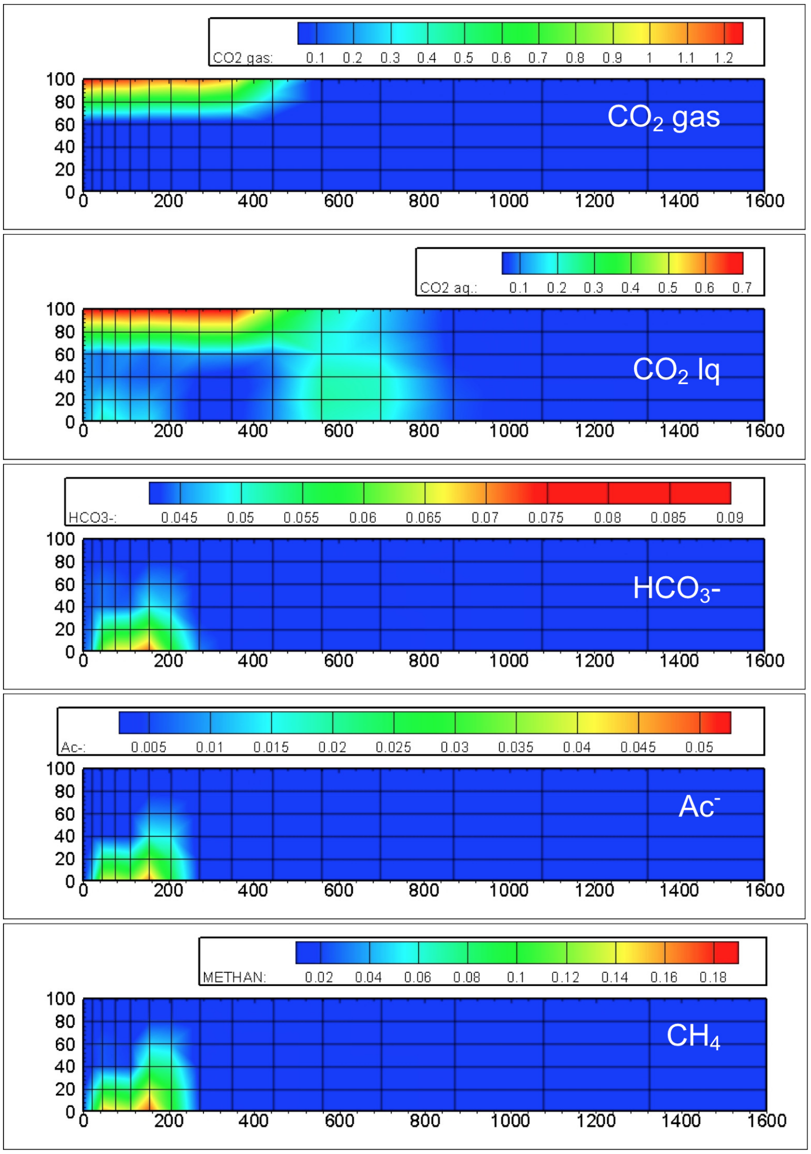


Figure 5 Mass distributions at 74.2 years after injection.
Scenario for calculation: CO_2 is injected for 10 years in 10^4 ton/year rate.
Then the reservoir was kept still for biological reaction.

5. Progress of risk & benefit assessment

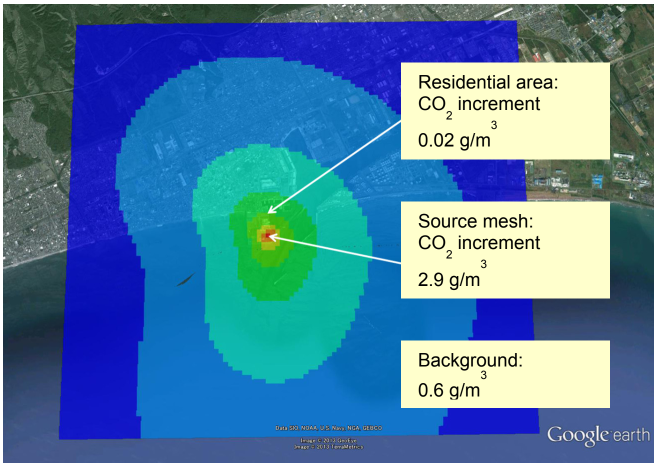
While more precise quantitative estimation of methane production is carrying out, we are preparing risk-benefit analysis. Our consideration involves not only quantity of CO_2 abatement and CH_4 production, but environmental and safety impact of Bio-CCS [4, 6].

We developed risk scenarios about CO_2 migration in relation with geological properties, condition of faults and pathways around well, using numerical simulation with TOUGH2-CO2 simulator. We also analyzed accident statistics of ground surface industrial facilities and oil/gas wells especially accidental leakage of CO_2 and methane leak. We estimated distribution of accident probabilities and accidental leak volume for 105 ton/year CO_2 injection. We assumed binomial distribution for accident probabilities, and obtained leak accident rate of surface facilities in 95% reliable level. We also assumed Gamma distribution for leakage volume and duration of wells, and estimated leak flow rate probability distribution. These accidental leak scenarios are applied to environmental impact studies and LCA analysis.

We evaluated scenarios of CO_2 leakage from ground surface to ambient air, using ADMAR2-AIST simulator (Atmospheric Dispersion Model for Exposure and Risk Assessment, AIST) [7]. Figure 6 shows an example of numerical simulation results. In this case, we choose on candidate CCS site in Japan, and applied long steady leakage like $10^4 \sim 10^6$ ton/year rate. Average weather conditions are used in the calculation.

For the same weather conditions and different CO_2 leakage rate, we obtained different concentrations, but shapes of CO_2 concentration contours were identical. (Relation is cubic root of ratio of two flow rates.)

In Figure 6, even if CO_2 10^6 ton/year (100% of 10^6 ton/year injection) will be released, increase in CO_2 concentrations in residential area (about 1km from injection well) is small (0.2 g/m^3), compared to ambient background ambient CO_2 concentration (0.6 g/m^3). Incremented concentration is equivalent level of normally observed CO_2 concentration of inside of residential buildings. Therefore, this scenario has none of impacts on human health.



Slow CO_2 leakage: 10^5ton/year.
Yearly average weather is applied to
ADMAR 2 –AIST simulator for numerical simulation.

Fig 6. Impact of CO_2 release accident on peripheral ambient air.

If we discuss produced methane gas related risks, it will depend on the quantities of the production from the well. As described in previous section, timescale of biological methanogenesis is different from CO_2 injection rate, and production volume is far smaller than injected CO_2 volume. Considering CH_4 release accident, CH_4 will be dispersed, but concentration is very low. The risks are negligible other than CH_4 is collected up to explosion limit (11%) ambient air.

Based on case study of well leakage accidents, we also set rapid CO_2 leakage scenario, like 10^6 ton/6 hours. To evaluate such rapid leakage scenario, we are on the course of extending ADMAR-AIST simulator functions now.

Setting seepage scenarios of under the seabed CO_2 storage, we numerically estimated dissolution of CO_2 in peripheral area of seepage point, and released volume of CO_2 from subsea to ambient air. We also evaluated diffusion of CO_2 in bay and seashore in multi-scales. As the result, we quantitatively estimated changes in CO_2 concentration and pH in seawater caused by CO_2 seepage. Now we are evaluating the impacts for sea animals. We are also evaluating impacts of CO_2 leakage against phosphorus and heavy metal desorption by way of both laboratory and field experiments. On the other hand, taking part of QICS and QICS II project in UK, we are evaluating CO_2 retention and buffering effects of seabed sediments. Now we are going to analyze relation between seabed sediments and desorption of phosphorus and heavy metals induced by CO_2 leakage to understand impact to sea animals.

6. Conclusion

To evaluate risk-benefit balance of Bio-CCS technology, we are preparing LCA (Life cycle assessment) of whole chain Bio-CCS operation. Analysis will include mass balance, energy balance, and environmental impact. Those results will be taken in count into the risk-benefit analysis.

To assist basic site evaluation and help understanding of Bio-CCS technology concept, we are preparing a prototype of Bio-CCS site evaluation system. All findings will be integrated in to it: cultivation condition of methanogenic geo-microbes, estimation method of methane generation quantities, environmental impacts of various risk scenarios, and benefit analysis of schematic site of Bio-CCS.

We expect that we will complete development of Bio-CCS site evaluation system at the end of the project duration. After that, we are going to extend applicable field of our Bio-CCS study into wider CCS site including EOR-CCS and CCS into aquifers.

Acknowledgements

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